VOLCANISM AND VEGETATION IN THE LESSER ANTILLES

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THE MAJORITY OF THE ISLANDS of the Lesser Antilles in the Caribbean archipelago are volcanic in origin. Two of the islands have active volcanoes which currently are dormant. However, Mt. Pelée on Martinique erupted in 1902 and 1930, and the Soufrière on St. Vincent erupted in 1902. Nine of the islands from Grenada, in the south, to St. Kitts, in the north, have active fumaroles or soufrières, indicating residual volcanic activity. Of the few volcanic islands without historic volcanic activity, Saba, Redonda, Union, and others show the classic forms of their volcanic origin and prehistoric volcanic activity (11, 13, 48, 60).

The eruptions of the twentieth century on Martinique and St. Vincent have been well observed, studied, and recorded. An extensive descriptive literature is available for the volcanic and seismic activities of the area. The literature regarding the geological phenomenon of fumaroles in the Lesser Antilles is less complete, although a specialized interest in utilizing the thermal power of one, the Qualibou soufrière in St. Lucia, has been recorded recently (8, 49, 50).

In nearly all of the geologic studies, as well as in many floristic, phytogeographical and ecological papers on the area, some mention is made of the effects of volcanoes and soufrières on the vegetation. These range from Perret's mention of the attempted use of the sensitive plant, *Mimosa pudica*, to record earthquakes, to the papers by Stehlé and Beard considering the progressive changes in the regrowth of vegetation on devastated volcanic slopes. The present paper, a survey of the nature of volcanic activity and its effects on the vegetation in the Lesser Antilles, is based on observations made in 1950 during a field trip which began in Trinidad, extended to the northern and western islands, and ended in Jamaica. Data and specimens were collected in and around many sites of past and present volcanic activity. More recent visits to the Lesser Antilles, particularly to Montserrat in 1961, have allowed comparative observations after an elapsed time, as well as the gathering of specific information. For comparison with the West Indies, I have had the opportunity of studying the effects of the recent eruptions of Kilauea and Kilauea-iki and of the various fumaroles on Mauna Loa, in Hawaii.

These trips, observations, and collections form part of a continuing study of the vegetation of the Lesser Antilles. I acknowledge with gratitude the support of the American Philosophical Society during the 1950 trip and that of the National Science Foundation for grants which have aided more recent work. Many people in the Lesser Antilles have aided my work in

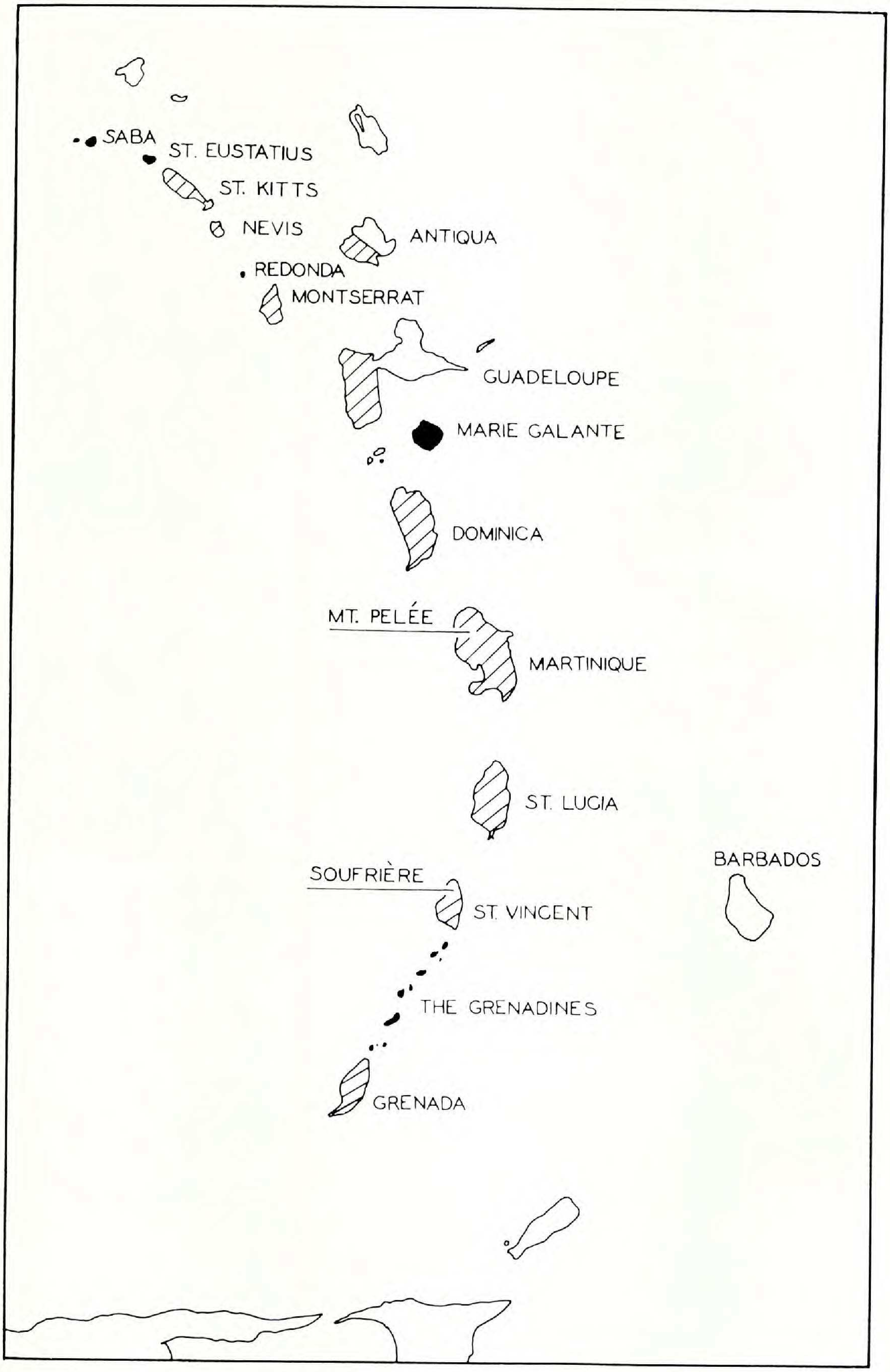
various ways. I mention in particular the assistance of Hugh McConnie, of St. Vincent; James Ross, of Grenada; Frank Delisle, now of Antigua; Kingsley Howes, of Montserrat; Harold Simmonds, of St. Lucia; John Knowlton, formerly of Dominica; and the late Malcolm Smith, of St. Kitts.

HISTORY OF VOLCANISM IN THE LESSER ANTILLES

Perret (46) has recorded the volcanological history of the Lesser Antilles. A chronology of the important eruptions is the following:

1692 – earthquakes followed by eruption on Mt. Misery, St. Kitts.
1694 – earthquakes followed by eruption on the Soufrière, Guadeloupe.
1718 – first recorded eruption of the Soufrière, St. Vincent.
1765 – earthquakes and gas emission on Dominica.
1766 – eruption of the Qualibou soufrière, St. Lucia.
1798 – earthquakes and eruption of the Soufrière, Guadeloupe.
1812 – great eruption of the Soufrière, St. Vincent.
1838 – eruption of the Soufrière, Guadeloupe.
1851 – earthquake and lateral outbreak of Mt. Pelée, Martinique.
1880 – ash eruption on Dominica.
1898 – start of three years of earthquakes and gas emission on Montserrat.
1902 – most destructive eruptions of Mt. Pelée, Martinique, and the Soufrière, St. Vincent.
1929 – eruption of Mt. Pelée, Martinique.
1934 – start of four years of earthquakes and gas emission on Montserrat.

The occurrence of earthquakes and actual eruptions is usually well recorded. Nevertheless, some of the earlier dates cited above have been questioned. Anderson (2), for example, cites both the picturesque report of the 1718 eruption of the Soufrière on St. Vincent, as given by Defoe (37), and the subsequent questions raised by the report. To the present day, the 1718 eruption is a questionable one. However, the geologists apparently have overlooked the work by Rev. Mr. Smith (64) who, while on Nevis, "heard six or seven dull bounces of noise resembling those of Cannon at a great distance pretty quickly following each other at the exact time of this Explosion: as the Sky was quite clear in the eye of the Wind, and as none of my acquaintance there took the same notice of the thing, I durst not venture to insist much upon hearing those dull bounces till I had seen Mr. Boyd." Mr. Boyd was previously identified as the captain of a merchant ship en route from St. Kitts to Barbados who noted that the sky grew dark and a horrible noise "far surpassing the loudest thunder" and a "falling likewise instantaneously so thick a Shower of Ashes, that the Sloop's Deck was covered two or three inches deep with them. . . . They in fright enough turned back homewards [and] . . . it was soon after found out, That a large Mountain in the Island of Saint Vincent . . . abounding in Veins of Sulphur and Brimstone blew up at once, viz. Woods, Rocks &c. all together, which must be allowed to cause a most dreadful Explosion." By contrast, the 1902 erup-



VOLCANIC AREAS OF THE LESSER ANTILLES. Diagonal lines indicate islands with active fumaroles. Mt. Pelée (Martinique) and the Soufrière (St. Vincent) are currently dormant but have erupted in the present century. Solid black areas are volcanic in origin. Unmarked areas are nonvolcanic islands.

tions of Mt. Pelée and the St. Vincent Soufrière were observed by parties of scientists from eight different countries, and, today, modern seismological stations record the minute signs of activity of these two dormant volcanoes.

The occurrence and duration of fumarole activity have been less accurately reported. Nugent's account of 1810 (42) is regarded as the original scientific observations for soufrières on Montserrat and other islands. Earlier accounts of hot springs do appear, with the emphasis generally placed on their curative medical properties or the ability to coagulate the protein of eggs. Père Labat (35), a French missionary to the Antilles between 1694 and 1705, recorded in six volumes his recollections of the Lesser Antilles. In 1696, he visited the Ance de Goyave in Guadeloupe and described the boiling fountains (*fontaines boüillantes*) in the bay, as well as in a neighboring swamp. He reported the water within a few feet of the coast to be warm enough to cook an egg held in his handkerchief. He attempted to determine the source of the heat and reported that, although the surface of the beach sand was without heat, when he dug to the depth of a foot he encountered sand and water too hot for his hand. This layer, he reported, smoked "comme on voit fumer la terre qui couvre le bois dont on fait le charbon." The fumes of sulphur were nearly unbearable. In a neighboring swamp he found a lake approximately 45 feet in diameter which boiled at the edges and also more strongly but less frequently in the center. The quiet periods, Labat reported, were of a duration sufficient to allow one to say both a *Pater* and an *Ave*. Odors of sulphur were strong here, too, and a sulphurous taste was present in the water. Even today, previously unknown areas of prehistoric soufrière activity are discovered in remote places on most of the Lesser Antilles, and new outbreaks of fumarole activity have been recorded in the last decade on Nevis and Montserrat. In general, the most active areas are well known, and the locations of the principal soufrières are to be indicated in summary for the various islands.

TYPES OF VOLCANIC ACTIVITY

Two basic types of volcanic activity occur in the Lesser Antilles. The most spectacular is the eruptive form so well recorded for Martinique and St. Vincent. Lava eruptions on these and other islands apparently occurred only in prehistoric times. The historic eruptions have been characterized by the forming of *nuées ardentes,* plus ash fall and mud flows. Hill (20) has described Mt. Pelée as an ash pile, a description which applies equally well to the Soufrière on St. Vincent.

Less spectacular, but of longer continuous duration in activity, is the fumarole. The fumarole is generally defined as a hole or vent (in or near a volcano) from which fumes are emitted. Subterranean as well as surface noise is present at most fumaroles. The gases produced may be saturated, ejecting with them large quantities of water, or they may be dry and either hot or cold. The dry, hot gases seem to condense atmospheric moisture some distance from the orifice, producing steam or clouds of vapor, thereby giving fumarolic areas an eerie appearance. With one exception, the gases and liquids produced by fumaroles in the Lesser Antilles are acid in reaction. This acidity is responsible for the chemical alteration, the coloration, and the physical decomposition of the soil and rocks characteristic of the areas around fumaroles.

A cluster of fumaroles is called a "soufrière," although in the Lesser Antilles this term is loosely applied to solitary as well as clustered vents, to mountains, and even to towns near sulphur-producing vents. A fumarole producing an odor of sulphur compounds is occasionally called a "solfatara" in this area. Technically, fumaroles are also classified according to their location as crateral fumaroles, when located in a volcanic crater, and noncrateral, when the point is lateral to a volcanic mass. Noncrateral fumaroles may be primary or secondary, depending on their association with the magmatic heat source. Representatives of all these types are to be found in the area. When the fumarole is depressed, surface waters may collect, and the dissolution of rock forms a mud pond or lake. Such bodies are also produced by the damming of valleys below fumarole areas by land slides, as in the case of the Boiling Lake in Dominica. Clear-water hot springs commonly found in alkaline areas elsewhere in the world have not been found in the Lesser Antilles.

VOLCANIC ERUPTIONS AND THE VEGETATION

The two active volcanoes on Martinique and St. Vincent are unique in producing only ash accumulations and a characteristic eruptive form termed *nuées ardentes* during the eruptions observed in modern times. The few lava flows or blocks recorded from the Lesser Antilles are of great age.

The recent and observed volcanic activity in the Lesser Antilles began with earthquakes and noise, the emission of gas and steam, and the ejection of ash and boulders. Some of the steam was derived from the vaporization of a crater lake from the caldera, at or near the summit. In the eruptions of the Soufrière in St. Vincent in both 1812 and 1902, either an eruptive force or a break in the crater wall produced a cascade of boiling water which descended the slopes to the sea. While this boiling torrent followed the established valley patterns on the mountain slope, its heat, volume, and speed killed and removed the vegetation. During its descent, it scoured the river valleys clear of accumulations of ash which thickened the consistency of the water and led to the reports of a lava flow. Anderson (2), who studied the 1812 deposits, concluded that it was a mud flow of accumulated ash and not a true lava flow.

The most destructive of the eruptive features of West Indian volcanoes have been the *nuées ardentes*. (See *Figs. 1, 2.*) The French seismologist Lacroix (36) proposed this term for the eruptions of Mt. Pelée and the Soufrière, and it has now become a standard term in all languages, although it is occasionally translated into English as "incandescent ash."

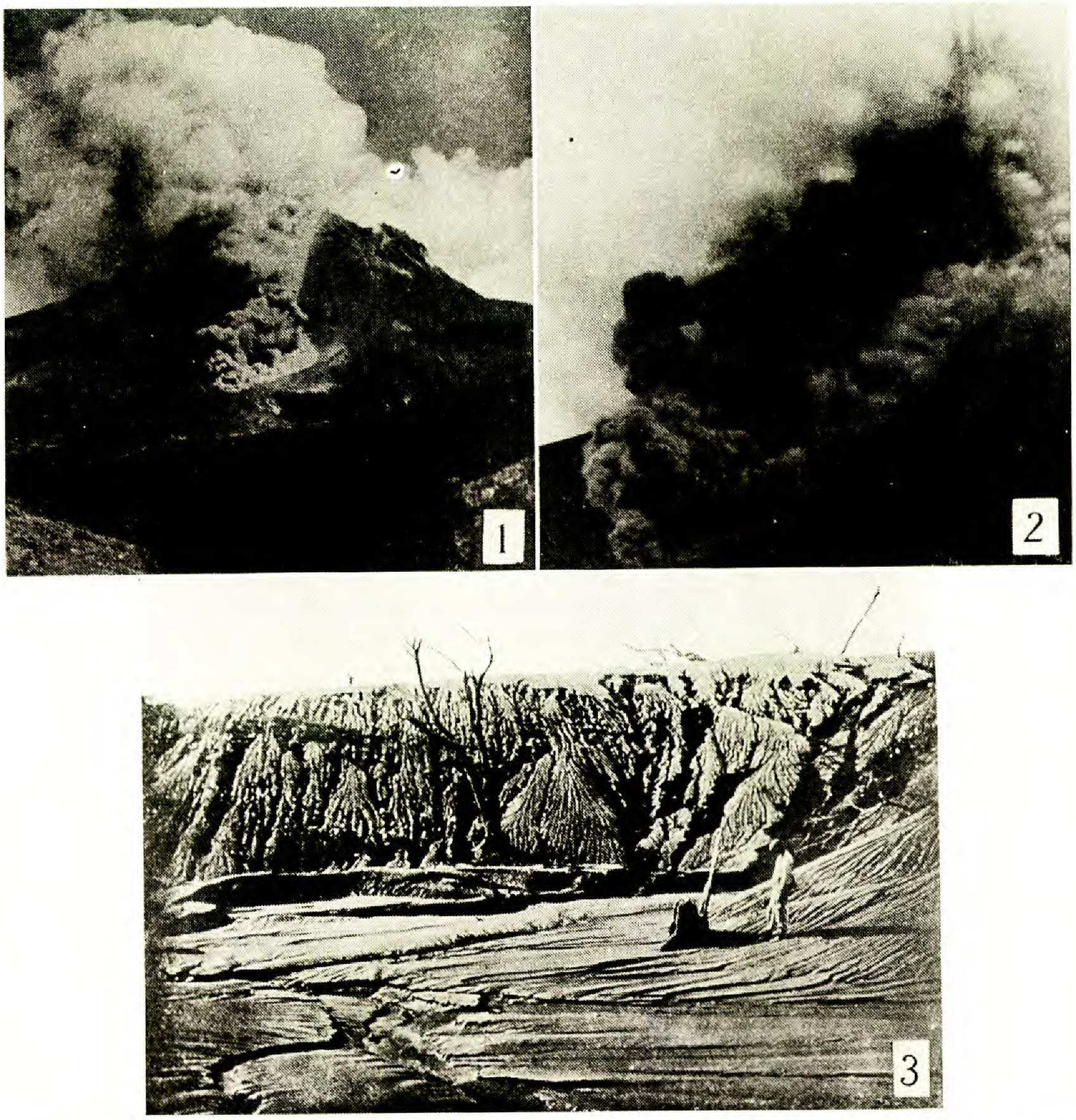


FIG. 1. *Nuée ardente* descending slopes of Mt. Pelée, April 13, 1931. Photo reproduced from Perret (44). FIG. 2. Initiation of *nuée ardente* on Mt. Pelée, 1930. Photo reproduced from Perret (46). FIG. 3. Ash accumulation on Wallibu fields, St. Vincent, 1902. Photo reproduced from Anderson and Flett (4).

Smith (63) has described the phenomenon as a "strange black cloud, which, laden with hot dust, swept with terrific velocity down the mountainside, burying the country in hot sand, suffocating and burning all living creatures in its path, and devouring the rich vegetation of the hill with one burning blast." Perret (46) explains its formation as follows: "In the acidic type [of volcano] its conduit normally closed because of the relative infusibility of the lava . . . the lava will have become surcharged with gases rising slowly from below, with possible assimilation from meteoric precipitation from above . . . the accumulated gas charge will, with eventual rupture of whatever restraint may have been imposed, go into paroxysmal explosive manifestation in the early stages of an eruption. A good instance of this is seen in the *nuée ardente*. . . . The viscous liquid has, through its own high gas content now coming out of solution in distributed gas vesicles, become autoexplosive as a whole and thus capable, on release, of lifting itself . . . clear out of its pocket, in a stupendous en masse expansion. It will be evident that this will convert what had been a liquid into an infinitely subdivided mass; in a word, largely into a cloud of vapor and solidifying particles. Its great weight will precipitate this upon the mountain flanks in a down rushing avalanche of very heavy materials at high temperature, emitting gas from every pore amid rising clouds of ash, and constituting what has been termed *nuée ardente*. This phenomenon was not described prior to 1902, the date of the destruction of St. Pierre, Martinique. . . . The velocity of the onrushing avalanche is phenomenal, and this fact is not unrelated to the continuing evolution of gas. Vapor films between all solid particles — from which particle the gas continues to be emitted during the 'life' of the *nuée* — effectively prevent all solid contacts, leaving the moving mass quite frictionless and capable of flowing upon the slightest inclines. . . . The original temperature (certainly on the order of more than 1,000 degrees C.) tends to be maintained by this insulating atmosphere." Perret also indicates that in a *nuée ardente* there is little if any free oxygen. As a result, no combustion occurs during its passage and materials are therefore carbonized and not burned.

The effects of a *nuée ardente* are localized but lethal to the life of the narrow belt over which it progresses. *Nuées ardentes* have been photographed from close range and have even been entered by volcanologists. Lava flows in Hawaii may leave little islands of vegetation (kipukas) undisturbed but surrounded with incandescent molten rock. Thus, too, in the case of a *nuée ardente*, areas adjacent to the descending cloud may be unaffected by the passage of the "incandescent avalanche." A study of the slopes of the Soufrière in St. Vincent today will show forests of massive trees cleft cleanly by the passage of a *nuée ardente*. On one particular slope there are 50–80-foot trees with trunks 2 to 3 feet in diameter and within a few yards the ash and scoria of the *nuée ardente* still barely colonized after 60 years. The *nuée ardente* carbonizes the vegetation in its path, while the residue of scoria left behind (in some cases 80 feet thick) retains its heat and kills the subterranean parts of the plants and the seeds and fruits on the ground. (See *Fig. 3*.)

Quite in contrast is the effect of the free fall of ash which may precede or follow the *nuée ardente*. The volume of free ash is tremendous and the distance it may be carried by the wind difficult to believe. Anderson and Fleet (3, 4) cite reports of a fall of ash on ships 830 miles east-southeast of Barbados, following the eruption of the St. Vincent Soufrière. Ash fell on Barbados, 100 miles away, at the rate of 3.94 tons per acre. Nearly all of St. Vincent was dusted or submerged in free ash from the eruption.

The term "volcanic ash" carries the popular connotation of a lightweight material. Perret states that this is not so, particularly in the ash derived from a *nuée ardente*. The crushing effect of the masses of ash is clearly documented, and the flattening effect on the vegetation implied. In the case of free-fall ash, the weight of individual particles may be less, but the cumulative weight equally great on any given area. Fields of arrowroot and other crops in St. Vincent buried under inches or feet of the cold free-fall ash did not recover. The accumulation of ash on leaves and branches caused defoliation and breakage of plants throughout the island. Although the size of the ash particles may have been small, the abrasive effect was noted in the puncture of leaves of crop plants and the removal of bark. A more modern report following the eruption of Parícutin in Mexico appropriately termed this "plutonic sandpaper" (47). The effects of the free ash on the vegetation is limited to abrasion, crushing, and smothering. The ash is generally chemically inert and without heat. The plants affected may recover or sprout from the base. Underground portions of the plants are not killed, and seeds germinate and may push up through the covering of ash.

The days which followed the eruptions of Pelée and the Soufrière have been reported as stormy. Heavy rain showers occurred. Perhaps the activity of the volcanoes caused the formation of the heavy rain clouds; but in any case, violent rain storms swept the area, and exceptionally heavy rain descended on the ash-covered slopes. Russell (52) noted that "instead of being a protection to the surface on which it rests, the fresh debris is in many instances of assistance in its more rapid erosion. On steep slopes, and even when the surface is nearly level, the rills formed during the numerous tropical showers quickly cut through the loose surface material, and aided by the angular particles in suspension, corrode the soil or rocks beneath. The rains, as it seems, are heavier than usual, owing to two causes: first, the great amount of water contributed to the atmosphere as steam, and second, the vast amount of dust blown into the air, each particle of which serves as a center for condensation." Riverbeds filled with ash and scoria were swept clean, scoured to new depths and often altered from their previous courses. As the ash deposits were removed, the lower soil areas, too, were eroded in sheets of mud which were deposited along the coast in fans recorded as 70 to 80 feet wide and seven miles in length. Subsequent earthquakes caused landslides in shaken and loosened terrain. North of Châteaubelair in St. Vincent, Russell reported "strips of nearly flat alluvial land, adjacent to the sea, have disappeared leaving fresh bluffs of loose debris some 30 or 40 feet high."

The revegetation of areas affected by volcanic activity has been the basis for classic studies in the case of Krakatoa. For the West Indies, Perret (44, 46) and Anderson (2) made initial studies and Stehlé (66) and Beard (6, 7) some recent summaries. A more detailed study is still required, with consideration given to the specific nature of the disturbance in each area. Perret noted the occurrence of "several mosses and fungi" within two years of the 1930 eruption of Mt. Pelée in an area affected by a *nuée ardente*. Judging from his photographs, the "fungi" are lichens of the genus *Stereocaulon*. Perret also noted the invasion of the "golden back fern" and a plant with "tiny blue blossoms, said to be invariably yellow in other localities." As both gold and silver forms of *Pityrogramma calomelanos* and *P. chrysophylla* occur in the Lesser Antilles, the scientific determination of plants cited in the geologists' reports are not to be trusted. Perret also commented that while the golden form of the fern occurred at lower elevations, only the silver form was found at higher level on the disturbed areas. Although the plant with blue blossoms can not be identified, *Pitcairnia spicata* is represented by the yellow-flowered var. *sulphurea* near craters and by the red-flowered typical form where volcanic fumes are not present.

Both Anderson (2) and Sands (53) visited the St. Vincent Soufrière in 1907, five years after the last eruption, and noted the species which invaded the area. Although Beard cites Anderson's paper, he quotes only from Sands' less critical report in which 154 species of plants were collected from low-altitude areas badly devastated by the eruption. Anderson, who was present during the eruptions, differentiates between areas affected by the *nuée ardente* and those affected by an ash fall. He states, "The incandescent avalanche swept down the Wallibu valley and spread out over the old fan or plateau at its mouth. It then turned south round the lower end of the Richmond Ridge and destroyed the Richmond Works and all the vegetation near them. The ash still remains to a depth of two to six feet in different parts, and the old roots are completely buried and thoroughly destroyed, but the avalanche was confined to the bottom of the valley and none of its effects are visible on either side. . . . The surface of the ash near the Works has not consolidated, but is rapidly breaking up under the influence of plant roots, and humus is being formed. . . . The chief new plants are Castor Oil (*Ricinus communis*), which grows in luxuriant masses along and around the ruins of the Works, and a plant, Cattle Tongue (*Pluchea odorata*) which has already formed flourishing bushes taller than a man. Besides these, Indigo (*Indigofera anil*), Sensitive Plant (*Mimosa pudica*), Guinea Grass (*Panicum maximum*), *Eupatorium odoratum*, and two grasses were also noted." Where the surface of the ash was consolidated, no vegetation can spring up; where it was broken by water or the hooves of animals the first invaders proved to be silver fern, grasses, and *Pluchea*. For areas covered with free fall ash, Anderson also related, "On the south slope leading up to the Morne Garu range the return has been considerable. The surface is still studded with the charred and bleached skeletons of trees, which appear to have been killed universally with the single exception of a small lateral valley north of the lower part of the Richmond Ridge, where a few palm trees in a sheltered position have recovered. The shrubs and herbaceous vegetation, which were all burnt level with the ground, are gradually returning, in many cases from the old roots, since the removal of the thin covering of ashes by the rain.

"The top of the Wallibu plateau was entirely devastated. The trees remain only as bleached trunks except a few which have recovered in sheltered positions at the ends and south edge of the plateau. The dead trunks show that the ash was never more than a few feet thick at the most, and the whole is now covered with a luxuriant growth chiefly from the old roots.

"At about 800 feet Tree Ferns (*Cyathea arborea*) become very abundant and large sheets of them are common, and generally it may be said that vegetation is luxuriant up to a height of about 1,000 feet, abundant up to 1,500, and very sparse above that height, with only a few grasses and silver ferns; higher up nothing but mosses and lichens are found.

"At the lower lip of the crater and just inside it mosses and lichens only are found. The mosses have been identified at Kew as: *Pogonatum tortile*, P. Beauv. and *Philonotis tenella*, Jacq. and the lichen as *Stereocaulon sp.*"

Beard (6) presented a study of the altitude zonation of vegetation types in undisturbed areas and, in comparison, the types he found on the slope of the Soufrière in 1940, approximately 40 years after the eruption. Beard found at 2,400 feet altitude that the "plants are knee high only, still composed of silver fern with now very stunted *Charianthus* and *Cyathea*, *Pitcairnia*, *Lobelia*, ferns and grasses.

"At 820 m. *Charianthus* and silver fern begin to thin out, and *Cyathea* is only 60 cm. high. Towards 900 m. the vegetation is simulating 'paramo' and is distinctly alpine in appearance. The ground is entirely and thickly covered with lichens, thallose, foliose and crustose. Higher plants are scattered and tufted and include the *Lobelia* and *Pitcairnia*, several grasses, a *Lycopodium* and a few ferns. *Cyathea* is now at most 30 cm. high, and the general vegetal covering is ankle deep only.

"At the highest levels one finds a tundra only. The stony ground is thickly covered with lichens and, in between, a few clumps of *Lobelia* and *Pitcairnia*. The lichens vary greatly in colour, being predominantly grey or orange, and having a striking appearance at a little distance."

It is interesting that the inside walls of the crater are covered with larger plants, right down to the water line nearly 1,000 feet below. Here *Baccharis cotinifolia*, *Gleichenia*, *Lycopodium*, ferns, grasses, and a few *Cyathea* occur in greater stature than at comparable levels on the outer slope of the crater.

Stehlé (66) described the revegetation of the slopes of Mt. Pelée and also determined that the altitudinal zonation existing before the eruption was re-established afterwards. On both Mt. Pelée and the Soufrière it was apparent that the *nuée ardente* completely removed all plants and their propagules. The ash fall, however, may have killed the portions of plants above the ground but allowed subterranean root and stem systems, as well as seeds, to survive and grow. In both cases, the revegetation was more rapid at lower elevations where a weedy flora was the first type to be established. At all but the highest elevations, lateral invasion from the areas of vegetation unaffected by the *nuée ardente* was apparent. At the highest elevations where no unaffected areas were present and the soil was isolated both vertically and horizontally from seed sources which would tolerate those environmental conditions, the reinvasion and re-establishment was slow, and often an unexpected composition was created. Lichens and mosses were the first and most successful invaders. Wind-blown spores of ferns were introduced, and the plants created pure stands of many individuals. Although spores of *Lycopodium* were eventually introduced, only scattered plants were found. The seeds of *Pitcairnia, Cladium,* and various grasses could have been distributed by wind to these new areas. Stehlé suggests that the fruits of *Charianthus, Lisianthus, Lobelia, Tibouchina, Ilex, Weinmannia,* and *Clusia* are distributed by birds or bats, and these plants are slow to become established in the devastated areas of high elevation. At lower altitudes birds, cattle, and man have played a role in starting new plants. Stehlé, for example, noticed the invasion of sugar cane on the slopes of Martinique and suggested that a wind-blown seed allowed this plant to be established on the scoria. Perhaps a node dropped by a wandering cane-chewing sightseer might be a more logical interpretation. The seeds of *Acacia* and *Mimosa* observed by Sands, Perret, and others were spread by cattle wandering over the newer ash accumulations.

It is of some interest to note that in all cases the growth of invading species appeared to be more rapid inside the crater of the volcano than at comparable levels on the outside. This growth can probably be associated with the greater protection afforded within the crater walls, as well as the more abundant moisture available on the less porous soil surface.

FUMAROLES AND THEIR EFFECTS

The occurrence of fumaroles, either singly or clustered as soufrières, can be reported for all the major islands of the Lesser Antilles from Grenada, in the south, to St. Kitts, in the north. The fumaroles are found at many elevations — submarine near Nevis, coastal on Montserrat, at low elevation on Grenada, and at the summit of the Soufrière (4800 feet) on Guadeloupe. The fumaroles are present in many vegetational types, including the thorn scrub of Grenada, old field vegetation on Dominica, mesophytic forests on Montserrat, and the volcanic facies on Guadeloupe. Active fumaroles can be determined from some distance by the production of heat, steam, and fumes laden with sulphur compounds. Near by, they show a characteristic destruction or absence of adjacent vegetation, if the fumes contain sulphur compounds, or an equally characteristic alteration of the rock texture and color. Extinct or dormant fumaroles may be recognized in open areas where mosses, algae, or perhaps a few higher plants cover the surface or where the softened rock in a restricted area reveals the former fumarole and its activity.

The activity of the fumarole may vary considerably in intensity over a long period of time or even in relation to the annual rainy or dry seasons. Some recurrence of fumarolic activity has been noted and associated with active volcanism on adjacent islands or with earthquakes of considerable geographic latitude. Within the Lesser Antilles are dormant fumaroles, those with long records of continuous activity, new ones, and those sporadic in their action.

Nearly all fumaroles are characterized by the emission of heat. Stehlé

(67) gives temperatures of the crateral fumaroles of Mt. Pelée as high as 700° C. Robson and Willmore (50) have published the most recent studies of heat emission from fumaroles in the Lesser Antilles. They have suggested as a base point the temperature of 24° C. for meteoric water or ordinary cold springs and for the air temperature. Steam temperatures from the Qualibou soufrière in St. Lucia have been measured as high as 185° C., while water outflow temperatures from ponds in the same soufrière varied from 63° to 96° C. On Montserrat, Robson and Willmore recorded the flow of water from Gages Upper Soufrière at temperatures of 34–86° C. from three sources and at Galway's Soufrière from 56° to 97° C. from two sources. Crater lakes, which may not show violent actions typical of fumaroles may show the effects of their proximity to sites of volcanism. The mean lake temperatures for the crater lake in the Soufrière of St. Vincent was 27.1° C., indicating at least a 4° rise in temperature due to the heating effect of submerged fumaroles. There is only one record of plant life in the boiling lakes of the Lesser Antilles, but this has never been verified in more recent observations. No animal life has been reported. Crater lakes, by contrast, have an algal or higher plant flora, and the crater lake on St. Vincent's Soufrière has recently been stocked with fish. The heat of water flowing from fumaroles or boiling lakes is soon dissipated. Blue-green and green algae, diatoms, and even sedges have been collected from outflows with temperatures of 56° to 85° C. within five feet of vents on several islands. Unfortunately, no identifications have ever been received from specialists who might name these collections of plants properly.

The direct emission of steam could have a noticeable destructive effect on the surrounding vegetation. Few plants could stand blasts of temperatures of 100° to 185° C. However, the direct blast of steam heat probably is of minor importance or none at all in comparison with soil heat, toxic gases, and cumulative acidity. Although MacGregor (39) gives in tabular form records of heat from soufrières on Montserrat, he also points out that the maximum temperature recorded depends on how far the thermometer can be pushed down the orifice against the gas pressure. Temperatures are higher below than at the surface, and such heat as is emitted is dissipated rapidly in the atmosphere.

For many of the West Indian fumaroles there appear to be few if any toxic substances included in the air being forced out at the present time. Around the fumaroles of Wotten Waven, in Dominica, the vegetation, instead of being adversely affected or killed, appears to grow more luxuriantly in the local area of higher heat and humidity. However, in many fumaroles there must be toxic substances, for the fumes have a definite effect on the vegetation. MacGregor and other authors have stated that the fumes kill the local vegetation. Even the names of the fumaroles and their areas suggest the toxicity. The largest soufrière on St. Lucia is known as "Qualibou," a name meaning "place of death," and some soufrières in Dominica are located in the "Valley of Desolation." It is clear that the fumes are often noxious and toxic to men and to plants. The death of two visitors to the Boiling Lake of Dominica has been substantiated. The geologist Perret was overcome by fumes while residing in his field station within Gages Lower Soufrière, and workmen on an earlier project in the same area were overcome. Although several geologists have attempted to collect and analyze the gases, the results are inconclusive. Romer (51) has reported the fumes from fumaroles on Mt. Pelée to contain only carbon dioxide, sulphur dioxide, and traces of hydrogen chloride; however, some fumaroles on Montserrat failed to give positive tests for carbon dioxide. Obviously the composition of the gases may vary with the nature of the activity of the fumaroles. Most fumaroles of the Lesser Antilles produce hydrogen sulphide, but all characteristically reveal an absence of fluorine, relatively few chlorides, and negligible amounts of boron. Perret described the gas of Gages Lower Soufrière and concluded it was "a gas having a traitorously pleasant odor, but extremely irritating to the eyes and respiratory passages. . . . It was highly unstable and decomposed into hydrogen sulphide and sulphur. It may have been one of the persulfides of hydrogen." Willmore (71) stated, "These vents emit a mixture of steam and sulphur gases which, during quiet periods, usually have a temperature a little below that of boiling water. During periods of abnormal activity the temperature of the exhalations often rises, and the predominant sulphur constituent may change from hydrogen sulfide to sulphur dioxide. — The tendency for the temperature to become stabilized near boiling point is readily explained on the assumption that the soufrière is supplied by hot juvenile gases which bubble through meteoric water on their way to the surface. The change in gaseous constitution during active periods is presumed to occur because the original magmatic gases undergo reactions on their way to the surface, so that the end products depend on the temperature and velocity of the flow." The absence of fluorides and the relatively small amounts of chlorides and boron support the conclusion that meteoric and not juvenile water is involved in most soufrières of the Lesser Antilles, at least most of the time.

The destruction of the vegetation around fumaroles, therefore, is apparently not caused by the chemical elements of the fumes or the water but by their nature as compounds. The various sulphur compounds in the presence of water can produce a series of acids. Litmus papers and "pHydrion" papers respond quickly, giving acid reactions. Perret reported that during the seismic crisis on Montserrat egg shells dropped in the fumarolic waters give rapid effervescence. Another mildly acid constituent of the fumarole fumes is hydrogen sulphide. The presence of this compound is evident, not only in the odor, but in the tarnishing of all silver brought into the vicinity. The town of Soufrière in St. Lucia is unfortunately in the lee of the Qualibou soufrière, and one is continuously aware of the derivation of the name of the town. Silverware tarnishes in the town of Plymouth in Montserrat which is downwind from the Gages soufrières. Perret depended on the reaction of lead-acetate paper to sulphur to record the intensity of such emission from the Gages soufrières, and during the same seismic crises even the lead paint blackened on ships in the roadstead.

The acids derived from the various sulphur compounds also affect the soil and rocks in the vicinity of the fumaroles. MacGregor (38, 39) concluded that "mineral changes brought about in the country rock render it locally pale to pure white in color." The pale color of soufrière areas renders them conspicuous and easily recognizable from a considerable distance. Accompanying the color change in the rock is a loss of structural hardness. Rocks in fumarole areas may retain their original shape and texture but become soft and nearly putty-like in consistency. The novice learns quickly of the treacherous footing in areas of fumaroles, where even the largest stones are not to be trusted.

When both hydrogen sulphide and sulphur dioxide are present, a chemical reaction may take place oxidizing the former and reducing the latter to produce water and crystalline sulphur. The deposits of sulphur crystals around the vents of Lesser Antillean fumaroles are colorful. Local needs for sulphur are easily met and at times small quantities of sulphur have been exported from the area. The commercial extraction of sulphur as a by-product of the use of steam for thermal power has been proposed (8).

EFFECTS OF FUMAROLES ON VEGETATION

During a visit to many of the fumaroles in the Lesser Antilles, it became apparent that there were areas around most fumaroles where no vegetation survived; that leeward from the vents certain plants were affected or killed by the emissions of the vent, while to the windward the same species approached or persisted much more closely; that certain species tolerate the effects of the fumaroles longer than others; that certain species invaded an affected area more readily than others; that some physiological change took place in the species which did grow successfully near the fumaroles in comparison with the same species elsewhere; and that the effects of the fumaroles on the vegetation were greater at certain periods than others. A review of the literature reveals that the earliest descriptions of the Boiling Lake on Dominica do not vary from observations made recently, and that Sapper's sketch (57) of the limit of devastation of vegetation at Galway's Soufrière on Montserrat differs little from a sketch map made last year. As long as the fumarole remains active and reasonably constant the effects on the vegetation are noticeable to a distance limited primarily by the terrain. Furthermore, the chemically altered rock and soil near the fumarole remain an inhospitable area for plants for decades, and revegetation is an extremely slow process.

However, new vents do open and I have had the opportunity of recording a sequence in the change of the vegetation near a new fumarole over a ten-year period on the island of Montserrat. In 1950, I visited both Gages Lower Soufrière, studied by Perret in 1934–37, and Gages Upper Soufrière, which was reactivated by an earthquake in 1937 when Gages

Lower Soufrière was dormant. Gages Upper Soufrière was active, but the vegetation around it appeared to have been stabilized in relation to the vents. Photographs were taken at both soufrières, notes were made, and specimens were collected approaching and adjacent to the devastated area. I returned to the area in 1961 expecting to determine the identity and the role of the plants which had successfully invaded during the past decade. At Gages Lower Soufrière I was not disappointed. Several four-foot plants of *Clusia alba*, as well as other weeds, were growing in the center of the ruins of Perret's field station. Young plants of *Andropogon*, *Philodendron giganteum*, and *Pitcairnia* were seen, and a coating of mosses colored many of the rocks.

The situation at Gages Upper Soufrière was another matter. New vents had opened in a thicket downstream from the previously affected area, affording an opportunity of determining the initial effects of a fumarole on previously undisturbed vegetation. The exact date of the inception of this vent is not known. Martin-Kaye (40) observed the area affected by Gages Upper Soufrière in 1954. A marker tree, a large buttressed rooted specimen of *Sloanea massonii* from which I had collected a specimen in 1950 was now dead, and only the stump remained some 50 feet inside the devastated area (*Fig. 13*). A vent had opened in the last decade directly under that tree, the base of which was now discolored white and yellow. The remaining stump was hot from the steam and wet and rotted, so that an 18-inch machete penetrated easily to its hilt, while "pHydrion" paper pressed against the sodden wood showed a pH of 1.5. The activity of the Gages Upper Soufrière had not only been extended downstream but up the hillside nearly to the ridge (*Fig. 12*). It apparently will be only a short time before the fumarole activity breaks through the crest of the ridge and effects a new drainage system.

In the newly affected area readings of temperature and the pH were taken on occasions between 8 A.M. and 5 P.M. over a period of two weeks with no significant variation in the figures. The vent of greatest interest (*Fig. 18*) was in a thicket composed of species of *Blechnum*, *Charianthus*, *Clusia*, *Cyathea*, *Ficus*, *Ilex*, *Miconia*, *Palicourea*, *Philodendron*, and *Symplocos*. No noticeable hole or pore had developed, and the steam appeared to be issuing from an area of dry soil about four inches in diameter. Outside of this small focal point some organic material was present but this was extremely dry. The diameter of the area of dry duff was approximately four feet. Outside of this area the debris on the soil surface was noticeably warm and moist, and dead and dying plants were obvious and readily identifiable. The effects of this new vent extended for a distance of only 20 feet. The temperature reading in the vent area was 94–96° C., a measurement obtained by inserting to a depth of three inches a laboratory thermometer calibrated to 250° C. In the area of dry and barren soil around the vent the temperature was 84° C. at a depth of three inches. The most tolerant plants in the area of wet, warm soil nearest the vent were *Blechnum*, *Clusia*, and *Philodendron*.

Beneath these plants the soil temperature was 54° C. Progressing outward on several radii, it was determined that species of *Ficus* and *Lycopodium* grew in soils at 48° C., while *Miconia* and *Palicourea* withstood 40° C. Beyond this point the soil temperature dropped to 30° C., and no killing was evident. The dead or nearly dead plants in soil temperatures of 40° C. and above were *Charianthus, Cyathea, Ilex, Miconia, Palicourea,* and *Symplocos*. About 100 yards away from this vent in the undisturbed forest, soil and air temperatures varied between 24° and 26° C. at different times of the day. It is apparent that one previously unrecognized factor in the death of plants around new fumaroles is the heating effect of the soil. Although the fumes from this small vent did discolor lead acetate paper they gave no reading on "pHydrion" paper. Litmus paper gave an acid reaction very slowly. The same papers used on the moist soil zone where plants had been killed gave readings of pH 1–1.5. The vegetable material present in the dry zone crumbled easily in my fingers. That of the moist zone, by contrast, was slippery or almost mucilaginous. The structure of the duff had been altered, and I judged from the ease with which my feet slipped that a heavy shower of rain would cause severe erosion. The areas unaffected by heat or low pH were more fibrous to the touch and more resistant under foot. Readings taken in the vegetable material in the unaffected forest showed pH 4–4.2. Hardy, Rodrigues, and Nanton (19) report that the majority of agricultural soils on Montserrat range from a pH of 6.1 to 7.4. Their two sets of figures for forest sites indicate pH readings of 4.3–4.8 (for lower montane rain forest soil on Frenchman's Hill) to a pH of 5.2–6.6 (for soils in a palm brake on Chance's Mountain). The initial killing effect of fumaroles may well be, first, soil temperatures beyond the range of tolerance of many species and, secondly, high acidity.

General observations were made on the vegetation within a few yards of the older area of devastation around Gages Upper Soufrière. Although the heat of the steam emissions could be felt in this area, it was not oppressive, and temperature readings were only a degree or two above those recorded deeper in the forest. The odor of hydrogen sulfide was noticeable, as was a higher humidity. Wet litmus paper did not indicate an acid reaction during a 30-minute exposure. Nevertheless, plants were dying and a slowly cumulative toxic effect of the fumes is the only explanation. The genera most susceptible appeared to be *Cyathea, Freziera, Hirtella, Licania, Palicourea, Peperomia, Philodendron* (except *P. giganteum*), *Psychotria, Symplocos* and *Weinmannia*. Species of *Gonzalagunia, Ilex*, and *Sloanea* appeared more tolerant and those of *Clusia* and *Ternstroemia*, as well as *Philodendron giganteum*, most resistant.

The oldest areas of Gages Upper Soufrière showed scattered plants of *Clusia alba, Cyperus ligularis, Philodendron giganteum*, and *Pitcairnia spicata*. It is not clear whether these plants were residual from the former vegetation or more recent invaders. They grew both as individuals and in groups. In numbers they were more abundant on the fumarole affected soil than in comparable areas of the undisturbed forests. Vents of two types were present in the areas where these plants grew. One type issued only fumes while the other had steam so laden with moisture that it condensed around the orifice and ran off, forming a small stream. The air issuing from the dry vents was recorded as high as 93° C., but the soil temperature immediately around the vent was 37° C. Incrustations of crystalline sulphur lined such orifices. The moist steam vents, however, gave readings of 37° to 70° C. taken in a comparable manner, and the "pHydrion" paper gave a reading of pH 1.5. Barren soil temperatures around these vents were 30° C. Temperatures recorded from around the root systems of *Philodendron* and *Pitcairnia* were 32° C. and the pH was 3. The highest water temperature recorded in any of the small pools within Gages Upper Soufrière was 94° C.

The Qualibou soufrière in St. Lucia afforded an example of vegetation stabilized to the long-term effects of fumes from fumaroles. This soufrière is located in a valley with a high hill on the windward side so that fumes from the fumaroles tend to rise along the hill face. The vegetation of this hillside consisted of stunted low plants of *Blechnum*, *Clusia*, *Cyperus*, *Gleichenia*, *Lycopodium*, and *Pityrogramma*. Just over the crest, in an area where the fumes were dissipated by the prevailing winds, the native forest flourished in an unaffected manner. The species which tolerated the fumes on the hillside were those with heavy cuticles, for the wax-rigid nature of the foliage was conspicuous in contrast to that of the same species growing in an area where they were unaffected by the fumes. The waxy coating on the leaves apparently made this vegetation more susceptible to burning, for a large fire scar dominated the face of the hill. In a few places a clear line of demarcation was evident between the plants which burned and those which only wilted down. This demarcation appeared to be associated with the plants exposed to the fumes and those protected from it.

An example of the periodicity of activity of fumaroles and the killing effect on the vegetation can be found on the slopes of the Soufrière on Guadeloupe. Stehlé (65) has described the units of vegetation which have been established at successive altitudes to the summit. His "Clusietum," "Lobelietum," "Pitcairnietum" represent, in part, tolerance of the component species to temperature, wind, and cloud cover but also to the pH of the ash terrain and to the effects of the fumaroles at the summit. During periods of little fumarole activity, the shrubs and trees may develop normally. When the fumaroles become active, the acid fumes will kill many of the branches and occasionally entire plants. Generally these plants recover by sprouting from the lower branches or the base, but the upper branches remain dead and leafless.

A unique fumarole area, perhaps more properly termed a hot springs, is found in Chambourg section of St. David's parish in northern Grenada. The twelve small bubbling hot springs apparently are influenced by the old volcanic mass below the crater lake, Lake Antoine. The soils appear to be coral limestone and a sandstone which includes volcanic ash. During certain seasons the waters of the springs overflow and several sizeable cones have been created. An alkaline litmus reaction was obtained from the waters collected in overflow pools. This, to my knowledge, is the only alkaline fumarole in the Lesser Antilles. No plants from the surrounding scrub of *Acacia*, *Acrostichum*, *Avicennia*, *Chrysobalanus*, and *Laguncularia* have encroached on the rock areas built up by the hot spring.

The Grenada hot-spring area is the only one in the Lesser Antilles venerated by the local people. One vent had an animal sacrifice placed there by religious cultists. Several springs had fresh or wilted bunches of flowers in the orifices. Candles and coatings of wax were present in the largest vent, along with a painting of the Sacred Heart. The late Father Bryan Proudman, who was my host in this area attributes the tokens to "shandoo" ceremonies.

CATALOGUE OF THE FUMAROLE AREAS OF THE LESSER ANTILLES

Grenada

THE GRAND ETANG. This crater lake is in the caldera of an old volcano. Beard (7) has described and illustrated this area and its vegetation. The lake temperature indicates the presence of some heat source. Sulphur odors are noticeable at times, and particles of sulphur occasionally appear on the surface of the lake. No effect of the heat or acidity can be noticed on the surrounding vegetation.

LAVERA HOT SPRINGS. (*Figs. 4, 5.*) About twelve small vents or pot holes near Lake Antoine produce an occasional weak odor of hydrogen sulfide. These are the only alkaline reacting springs that I have encountered. The vegetation has not encroached on the sheets of hard rock formed by the overflow from these springs.

St. Vincent

THE SOUFRIÈRE. Interest in the eruptive volcano on St. Vincent centers on the accuracy of the reports of its eruption in 1902. Prior to that time, eruptions have been recorded for 1718 and 1812. Reports of the former eruption have been considered by Anderson and Flett (4). They point out that while Huggins (32) discredits such reports, Defoe (37) only in part exaggerates in his story, which may indeed have been based on fact. The letters of Rev. Smith (64) may be considered corroborative evidence that the Soufrière did erupt in 1718.

Mr. James Anderson apparently was the first white man to ascend the volcano. In an account published in 1785 (1) he described the summit. "We found very little obstruction in our way up until we got to the place where I returned, and there, for about a quarter of a mile, we had considerable difficulty to clear our way through grass and ferns. After we came within a quarter of a mile from the top, we found ourselves in another climate all at once, the air very cold, and the vegetable productions changed; here was nothing but barrenness over the whole summit of the mountain. On the confines of the grassy region and the barren I found some beautiful plants. Moss grows here in such plenty that I frequently sunk up to my knees in it. This is the only place in the West Indies that produced any moss that I have seen. About noon we gained the top of the peak . . . when in an instant, we were surprised with one of the grandest and most awful scenes I had ever beheld." For the crater Anderson reported, "In the centre of the bottom is a burning mountain, of about a mile in circumference, of a conic form, but quite level. . . . From the external appearance of this mountain, I imagine it has only begun to burn lately, as on several parts of it I saw small shrubs and grass, which looked as if they had been scorched and burnt. . . . On two opposite sides of the burning mountain, . . . are two lakes of water."

An anonymous account published in the *Evening News* of July 30th, 1812, is reprinted by Anderson and Flett (4). This account described an ascent of the Soufrière on April 26th, only a few hours before its eruption at noon on the 27th. On viewing the crater, the anonymous report stated, "Exactly in the centre of this capacious bowl rose a conical hill, about 250 or 300 feet in height, and about 200 in diameter, richly covered and variegated with shrubs, brushwood, and vines about half-way up, and for the remainder powdered over with virgin sulphur to the top. . . . The precipitous sides of this magnificent ampitheatre were fringed with various evergreens and aromatic shrubs, flowers, and many alpine plants. On the north and south sides of the base of the cone were two pieces of water, one pure and tasteless, the other strongly impregnated with sulphur and alum." A comparison of the two reports indicates a secession of the activity of the cone and a re-establishment of the vegetation. The eruption changed all this, for as Shephard (62) stated, "all the former beauty of the Soufrière was, of course destroyed; the conical mount disappeared, and an extensive lake of yellow-coloured water, whose agitated waves perpetually threw up vast quantities of black sand, supplied its place." Hooper's account in 1886 (24) suggests that a single lake remained in the crater. Anderson and Flett (4) reported that the crater "contained three small lakes of water, greenish and turbid, that in the southeast corner was throwing up jets of mud and steam with a hissing noise." In the years which followed, an accumulation of rain water apparently raised the surface of the three lakes and made them confluent. Beard (6) found only one lake in the crater during his visit in 1940, and such is the situation today. The southeast corner of the lake, however, is often discolored with suspended material and flakes of sulphur, indicating that all is not quiet in the fumarole area.

Beard has described the progress of plant succession on the Soufrière in a paper published in 1945. A new study, now that an additional two decades have passed, appears to be in order. I visited the summit of the Soufrière in 1950 and found sufficient differences from Beard's description to suggest that the initial invasion of plants had been successful, that a favorable environment had been created, and that rapid changes were then taking place. At that time, the floral composition of the summit was closer to that described by Hooper prior to the 1902 eruption, with the sole exception of an abundance of fleshy liverworts unmentioned by either Hooper or Beard.

St. Lucia

THE QUALIBOU SOUFRIÈRE. (*Figs. 20, 21.*) This appears to be the only active soufrière on the island of St. Lucia and is situated about a mile and a half southeast of the town of Soufrière. Hooper visited the area in 1886 and reported briefly that "the exhalation . . . has reduced the vegetation on both sides within reach to a carpet of brake fern." In 1903, Sapper (56) and, in 1904, Hovey (26) described the area as between two and three acres in extent, but neither made reference to the vegetation. In 1949, Beard (7) noted that a specialized vegetation was found around the Sulphur Springs (the Qualibou vents). "Clumps of *Pitcairnia* are as usual found nearest to the vents with some *Cyperus ligularis*. Farther out, these are joined by various species of ferns, principally *Blechnum serrulatum* dominated by large clumped bushes of *Clusia plukenetii* and *C. alba*. The whole hillside above the Springs is carpeted with *Blechnum* ferns with an occasional *Clusia*."

The vegetation around the Qualibou soufrière appears to be completely stabilized. Algae are found in dense mats in the drainage of the hot springs. *Cyperus* and *Eleocharis* plants are common in shallow warm pools of seepage areas. None of the larger plants seen in the area showed any damage from the constant emissions of the fumaroles.

Recent interest has centered in the possible utilization of the thermal heat for generating electricity. The reports of Bodvarsson (8) and of Robson and Willmore (49) are pertinent to this problem.

Martinique

MT. PELÉE. The destructive eruption of Mt. Pelée in 1902 eliminated the town of Saint Pierre, killing all but one person. The latter stages of this eruption, as well as that which occurred in 1930, are well described by numerous authors (2, 3, 29, 36, 39, 44, 52). Bibliographies of significant publications are given by Hovey (28) and Russell (52). Few specific data are available on the regrowth of the vegetation, and a modern survey seems desirable. Stehlé visited the area and published in 1938 a general consideration of the regrowth (66). He recognized conditions comparable to those of Guadeloupe, excepting the sulphur fumes, and suggested that the vegetational zones were a "Clusietum martinicense," a "Lobelietum martinicense," and a "Pitcairnietum martinicense." Stehlé attributed to larger animals the introduction of *Mimosa pigra* and *Acacia tortuosa* to the areas of recent lavas. Birds, he felt, accounted for the introduction of *Ficus*, *Melia*, *Trema*, *Tetrazygia discolor*, and *Miconia striata*. At the lowest elevations on new lavas, Stehlé found common weedy species of *Crotalaria*, *Cassia*, *Emilia*, *Euphorbia*, *Bidens*, *Ageratum*, *Indigofera*, *Pluchea*, etc. Slightly higher and probably introduced by wind were plants of *Ochroma pyramidale*, *Ceiba antillana*, and *Tecoma stans*. Near the top of Mt. Pelée, Stehlé reports the occurrence of two species of *Desmodium* and single species each of *Stenotaphrum*, *Erigeron*, *Sauvagesia*, *Mikania*, *Arthrostemma*, *Hypoxis*, *Cuphea*, *Rubus*, *Phenax*, and *Cyperus*. The majority of these are not found at higher altitudes in undisturbed vegetation on Martinique or nearby islands. No information is available on the length of their persistence. Stehlé indicated that the most powerful colonizers were *Pitcairnia bracteata*, *Guzmania plumieri*, *Tibouchina chamaecistus*, *Baccharis cotinifolia*, *Pityrogramma calomelanos*, and two species of *Epidendrum*.

Thermal springs are recorded from the vicinities of the towns of Frégate and La Redoute, along the coast near Marigot, and on the slopes of Mt. Pelée above Macouba. I have not located descriptive literature regarding their activity as fumaroles or the vegetation around them.

Dominica

The earliest record of fumaroles on Dominica appears in Atwood's account of the island published in 1791 (5). His vivid, but questionably accurate description stated, "These sulphurous mountains are certainly among the most wonderful phaenomena of nature, and command our astonishment and admiration. To see vast tracts of land on fire, whose smoke, like clouds, stretches far around; brimstone in flames, like streams of water issuing from the sides of precipices; in the vallies large holes full of bituminous matter, boiling and bubbling like a caldron; the earth trembling under the tread, and bursting out with loud explosions, are objects truly terrefic to the beholder; who, on the spot, are struck with awe and admirations, on viewing such dreadful works of the Almighty, who causes them to exist, for purposes only known by him." Edwards (15) also reported about Dominica that "several of the mountains contain unextinguished volcanoes, which frequently discharge vast quantities of burning sulphur. From these mountains also issue springs of hot water. . . ." There are no reports of eruptions on Dominica in historic times, and these two early descriptions can not be definitely located geographically. It is possible that these both refer to the imposing Valley of Desolation and its famous Boiling Lake, and represent its earliest record. The discovery of the Boiling Lake is generally credited to Dr. H. A. Nicholls around 1880. Nicholls' route was soon followed by Ober (43), Johow (33), and others, all of whom comment in one way or another on the nature and composition of the vegetation in the Valley of Desolation and around the Boiling Lake.

Hovey (30) and Earle (14) were the first to consider the geology of the area. Later in the twentieth century Domin (13a) and Hodge (21, 22) studied the vegetation of Dominica, and both wrote extensively on this subject. Hodge has said of the Valley of Desolation, "The combined sulphurous fumes of all the vents and fumaroles have had a blighting effect far up the slopes, wherever they have come against the vegetation.

The end result has been the formation of what is known locally as the Valley of Desolation.' [See *Fig. 6.*] Along the ridges above lies Elfin woodland but in the valley only patches of it remain and in these *Clusia venosa* and an *Ilex* seem best able to tolerate the noxious gases. In the proximity of the fumaroles vegetation is absent or sparse and except for the colorful algae to be seen in the warm water of the streams, is apparently unable either to tolerate the noxious fumes or to root in the mineral-impregnated soil. The only pioneer species observed close to the vents were the bromeliad *Pitcairnia spicata* var. *sulphurea*, a grass, *Ischaemum latifolium*, and occasional plants of *Dicranopteris bifida*." Hovey (30), Sapper (56), and Robson and Willmore (51) give data on the water temperatures of the Boiling Lake.

Earle (14) reported additional soufrières in Dominica at Ravine D'Or (Layou Valley), Morne au Diable (Portsmouth), Laudat and Soufrière villages, and Wotten Waven. He states, "All of these are insignificant besides the Grande Soufrière, though the Wotten Waven springs are quite numerous and besides a few violent fumaroles also display small mud volcanoes."

At Wotten Waven I was able to visit the fumarole area which is located in an old field now devoted largely to pasture. The fumaroles at the time of my visit were noisy and emitting steam, but almost without sulphurous odors. The high humidity and heat appeared to encourage plant growth, and the shrubs of *Clusia alba* were more luxuriant than specimens we had passed a few yards away (*Fig. 7.*)

The fumarole area behind Soufrière village was represented by an enormous scar on the hillside where landslides had recently exposed fresh surfaces and obscured some of the vents. The fumaroles were not noticeably active, and although the odors of sulphur dominated the air, there was no evident destruction of the vegetation. The area was well stabilized, but few plants other than species of *Blechnum*, *Dicranopteris*, and *Cyperus* had invaded the areas.

Guadeloupe

THERMAL SPRINGS. The island of Guadeloupe is reported to have thermal springs along the coast at the towns of Boüillante, Monchy, and Pigeon; somewhat inland near La Lise and Dolé; on the slopes of the Soufrière near Baines Jaunes; and at the summit of the Soufrière. All of these are on Basse Terre and probably are associated with the volcanic massif of the Soufrière. I have not visited the thermal springs at low altitude and have been unable to find any descriptive literature regarding them or the vegetation surrounding them.

The oldest reference to hot springs and fumaroles is found in Père Labat's writings. His description of the thermal springs of "Ance de Goyave" presumably refer to the area currently called Boüillante and not to Goyave on the west coast. Labat also climbed the Soufrière and described the stunted vegetation near the summit. A trip from St. Claude to Baines Jaunes and along the old carriage trails past the warm and cold baths to the summit of the Soufrière suggests that few changes have occurred in the intervening 260 years (*Figs. 8, 9*).

Stehlé (65, 67, 68) has published several admirable treatments of the vegetation of the slope of the Soufrière. He indicates that the effects of high altitude and of the sulphur vapors cause a limitation in height of plants but seem to encourage the development of many lateral branches. He also states, "Les gaz sulfureux émis par la Soufrière sont néfastes à la végétation environnante, qu'ils détruisent peu à peu." Stehlé concludes that the species which exist in this environment are particularly interesting and rare. Many are thought to be endemics, but as more is known of the vegetation of the high mountain peaks from St. Kitts to St. Vincent it becomes increasingly difficult to separate those species which are restricted to high elevations on the ash of volcanic ejecta and those which are there because of their tolerance to fumarole emissions. However, the red-flowered form of the bromeliad *Pitcairnia spicata* occurs at high altitudes on St. Kitts, Guadeloupe, Dominica, Martinique, and St. Vincent, while the yellow-flowered form, *P. spicata* var. *sulphurea*, has not been found on St. Kitts and occurs on the other islands in areas influenced by the crateral fumaroles. The endemic species of these high mountains are not the most distinct of species, and recent collections from other islands have indicated that their distribution is wider in the Lesser Antilles than has been previously reported.

Montserrat

GALWAY'S SOUFRIÈRE. (*Fig. 15.*) One of the earliest accounts of the soufrières on Montserrat was made by Dr. Nicholas Nugent, an honorary member of the Geological Society of London who visited Montserrat in 1810. His point of view in visiting Galway's Soufrière was entirely geological, but his description applies to the present as well. "A rugged horse-path was traced along the brink of the ravine, which we followed amidst the most beautiful and romantic scenery. At the head of this ravine is a small amphitheatre formed by lofty surrounding mountains, and here is situated what is termed 'The Sulphur.' Though the scene was extremely grand and well worthy of observation, yet I confess I could not help feeling a good deal disappointed, as there was nothing like a crater to be seen, or anything else that could lead me to suppose the place had any connexion with a volcano. On the north, east and west sides were lofty mountains wooded to the tops, composed apparently of the same kind of porphyry we had noticed all along the way. On the south, the same kind of rock of no great height, quite bare of vegetation, and in a very peculiar state of decomposition. And on the south-eastern side, our path, and the outlet into the ravine. The whole area thus included, might be three or four hundred yards in length and half that distance in breadth."

Karl Sapper visited Montserrat in 1903 (57) and visited both Gages and Galway's soufrières. He published a sketch map of Galway's Soufrière indicating the principal fumaroles where he recorded temperatures of 34.2–93.2° C. and commented on the production of hydrogen sulfide by each. Sapper estimated the area of destruction of vegetation as between three and four hectares. MacGregor (39) reproduced Sapper's sketch-map and concluded that the site of fumarole activity had changed by the time of his visit in 1936. Perret also visited Galway's Soufrière during the volcanic crisis in Montserrat in 1934. His description of the area is meager, for he concluded that, "Galways Soufrière was a more ordinary solfatara having less chemical activity and water of less acidity — altogether, a vent less capable of serving as an indicator of increasing volcanic activity than the more accessible Gages Soufrière." He did note that the water from Gages Soufrière had an acid content ten times as great as that from Galway's. My tests in 1961 with "pHydrion" paper gave a reading of pH 5 for the waters in Galway's fumaroles and 1.5 for those in Gages.

Sapper commented only on the dead and dying vegetation in the vicinity of Galway's Soufrière, and his outline map of the area of activity and destruction has recently been questioned by Martin-Kaye (40), who felt from seeing MacGregor's reproduction of Sapper's map that the main stream was in reality the southeast stream as drawn by Martin-Kaye (40). I find it difficult to agree with this conclusion and suggest that Sapper and MacGregor are correct. Certainly the locations of the principal vent are similar on the two maps in relation to the area of destroyed vegetation.

Martin-Kaye has reproduced temperature records at Galway's Soufrière taken by the Montserrat Department of Agriculture from 1936 to 1952. My own reading taken in January, 1961, showed a vent temperature of 96° C. (200° F.) and pool temperatures 83° and 77° C. (180° and 170° F.), respectively, for the pools where, I was told, the temperatures were generally recorded.

The vegetation at Galway's appears to be completely stabilized. The prevailing winds blowing down the mountain gorges across the soufrière and towards the sea apparently have carried the toxic fumes for years at definite elevations. Plants have developed in the lee of fans, piles of scree, and even behind boulders. To the windward, the vegetation is unaffected, and not at all stunted. The principal plants nearest the soufrière were *Clusia*, *Freziera* and *Ternstroemia*. Within the soufrière proper the existing and often flourishing plants belong to the genera *Andropogon*, *Clusia*, *Cyperus*, *Philodendron*, *Pitcairnia*, *Pityrogramma*, and *Ternstroemia*.

GAGES LOWER SOUFRIÈRE. (*Fig. 14.*) Nugent does not mention Gages soufrières and Shafer's (61) description of his visit to Montserrat speaks so generally of the three soufrières that one can not place his actual visit. Gages Lower Soufrière is said to have originated in 1896 following a cloudburst and to have been moderately active during an earthquake series in 1898. Perret's visit to and study of Gages Lower Soufrière during its period of renewed activity beginning in 1933 is well recorded. Gages Lower Soufrière consists of two parallel valleys, one old and inactive, the other a "new rift" which opened around 1930. The one valley remained active through 1935, but by the 6th of May, 1937, the gas phase had subsided and the water from the gorge was nearly chemically inert. I visited this area in 1950 and again in 1961. Little change was observed in the first visit from the condition shown in Perret's photographs. In 1961, only minor fume emissions were noticeable with faint odors of hydrogen sulfide with sufficient heat and steam to cloud one's glasses. Fume temperatures at the most active vents were 94–96° C. The area of devastation, which Perret judged to be 600 feet long and 350 feet wide, had not increased, but by 1961 an occasional patch of green from prothallia or young gametophytes of mosses was evident, with an occasional plant of *Andropogon, Capraria biflora, Clusia,* or *Cyperus* present in the valley. On the limonitized zone at the head of the valley grasses and sedges were becoming more abundant, apparently developing from seed sources above the devastated area.

GAGES UPPER SOUFRIÈRE. (*Figs. 10–13, 18, 19.*) Accurate dating is not available for the age of Gages Upper Soufrière. Sapper (57) visited it in 1903, and Perret indicates that it was dormant prior to the earthquake of November 11, 1935, when its activity increased enormously. Perret does not go into detail on his observations on Gages Upper Soufrière, although he delayed his departure from Montserrat to study this new outbreak. He does indicate that the temperatures were 99° C. in the steam vent and 96° and 98° C. in the pools. His illustrations, and particularly *Fig. 31* reproduced here, are noteworthy for the remnants of the vegetation shown. Clearly, the area of Gages Upper Soufrière had been relatively small prior to the 1935 activity, for the density of the vegetation indicates a recent kill. Perret noted that there was a threat for Gages Upper Soufrière to "extend its domain by reason of gas emission and rain erosion." Martin-Kaye's observations and map for his visit in October, 1954, led to the conclusion that "much of this area has comparatively recently opened up as many rotted tree stumps are still to be seen more or less in the position of growth." My own comparative observations already mentioned were made in 1950 and again in 1961 and lead only to the conclusion that Gages Upper Soufrière is not only as active as it has been in the past but is continuing to increase to the southwest and may well cross the ridge into the next valley. The area devastated at present is about eight acres at an altitude between 1300 and 1400 ft. along the stream bed, but extending up the hill to around 1700 ft.

TAR RIVER SOUFRIÈRE. MacGregor (39) has illustrated in his *Figure 37* the appearance of the "New Cow Hill soufrière" (Tar River) shortly after its inception in 1936. The fumaroles apparently appeared in the center of a banana plantation. When Martin-Kaye and Willmore visited the area the fumarole was relatively quiet, and only about an acre of vegetation was affected by the fumes. In 1961 steam and fumes were not apparent from a convenient observation point on the slopes leading to English's Mountain.

LANG'S SOUFRIÈRE. (*Figs. 16, 17.*) With the expert guidance of Kingsley Howes we visited the recently discovered Lang's Soufrière on the north flank of the Soufrière Hills above Paradise Estate. The soufrière itself is essentially dormant, giving only occasional indication of hydrogen sulfide and some degree of heat. It is located at the head of a deep ravine, and landslides not of recent time have covered the actual fumaroles. The decomposition of the rock in the area, plus the occurrence of one large dead specimen of *Sloanea* and the abundance of *Philodendron giganteum* attested to the past activity of this fumarole.

OTHER SOUFRIÈRES. Through the Soufrière Hills are other indications of dead or dormant fumarole areas. Several were seen in Gages Gut en route to Gages Upper Soufrière. Neither fumes nor heat is emitted from these areas at the present. The older ones were green with mosses and lichens, and the younger ones still showed the color of the altered rocks. These fumaroles were apparently never of major importance, for the surrounding vegetation was neither affected nor characterized by the genera usually found in active areas. Mulcair Soufrière was known by reputation to the local people, but, as Martin-Kaye discovered, it seems to be inaccessible, for no local individual was capable of guiding me to it.

HOT WATER POND. This coastal pond is thought to be heated by subterranean springs, possibly the drainage from the Gages soufrières. It did not support any unusual plant life nor was the surrounding vegetation affected in any way.

St. Kitts

Martin-Kaye (40) supplies the only references I have encountered to fumarole activity on the island of St. Kitts. My visits have been at times when the cloud cover made any ascent of Mt. Misery of doubtful value. Martin-Kaye reports however, that the crater of Mt. Misery is between one-half and three-fourths of a mile in diameter at the rim, 500 to 600 feet deep, and possesses a small shallow lake in the southwest part of the floor, which "except in the vicinity of two small areas of fumarole activity, is otherwise covered with vegetation." Martin-Kaye also reports that "now defunct fumarolic activity has caused rock alteration at Rainbow Cliff, Frigate Bay where variously colored ochres are associated with yellowish, brownish and grey clays, kaolin, some gypsum and probably opal powders and alunite as are associated with the active soufrières in Montserrat, Nevis, Mt. Misery itself and elsewhere in the Lesser Antilles." Regrettably no data on the surrounding vegetation are available.

Nevis

The Rev. Mr. Smith (64) in a series of letters presents some of the earliest records of the natural history of Nevis. In his second letter he refers to a hot river and to baths "supposed to flow from the sulphur ground which is not above three quarters of a mile higher in the country." He also notes that "In my parish of St. John in the Island of Nevis, there is a considerable spot of sulphurous ground on the south side, at the upper end of a deep rupture in the earth vulgarly called Sulphur Gut, which is so excessive hot . . . as to make us immediately feel it through our Shoe Soals." Rev. Smith refers to another at a "place two miles and half south-ward of Charles Town" and reports that "a new hot spring was in 1718, discovered in Windward Parish, upon clearing of a wood . . . just above Camp-ground."

Bryan Edwards (15) said for Nevis, "That the island was produced by some volcanic explosion, in ages long past, there can be no doubt; for there is a hollow, or crater, near the summit, still visible, which contains a hot spring strongly impregnated with sulphur; and sulphur is frequently found in substances, in the neighboring gullies and cavities of the earth." In his excellent treatment of the geology of the Leeward Islands, Martin-Kaye has reported two active soufrières on Nevis at Farm's Estate and Cades Bay, the latter first noticed in 1953. In addition there is some gas seepage noticeable in the Belmont area and thermal pools at Bath Springs near Charlestown and in the Camp Springs area. The thermal pools apparently are those described by the Rev. Smith, indicating an activity of nearly 250 years.

The Farm's Estate Soufrière is both old and relatively quiet. Hydrogen sulphide odors and wisps of steam are noticeable. Willmore recorded temperatures of 42–44° C. in small fissures and temperatures of 96° C. in a vent. Apparently the vegetation has been affected by the activity of the fumaroles but has now become stabilized.

The Cades Bay Soufrière, according to Martin-Kaye, was first noted in 1953 when the "vegetation began to die and hydrogen sulfide was evident." In six months an area twenty by thirty feet containing sunken boiling steam holes had developed and odors of sulphur dioxide were evident. Shortly thereafter several areas became confluent by the loss of vegetation and a barren area of about 1.5 acres was produced containing small pools with water registering a temperature of 118° F. Martin-Kaye reports that in 1958 the vents "seem to have mainly concentrated in one small bubbling pool a few feet across" and that the "vegetation had re-established itself over the western part." Regrettably no specific information on the nature of the vegetation of the area is available.

SUMMATION AND COMPARISONS

Volcanism, either eruptive or fumarolic, is destructive to vegetation, as ample examples show in the Lesser Antilles. *Nuées ardentes*, characteristic of recent eruptions, are totally destructive of plant life, and ash falls less so. The revegetation of ash-covered areas is related to the type of destruction but also to the altitude of the area considered and its proximity to sources of new plants. At lower elevations or adjacent to undisturbed areas invasion by weedy species is rapid. Plants covered only with free-fall ash appear to sprout rapidly from the basal portions and quickly supply a covering vegetation. At highest elevations where a specialized vegetation occurs the re-establishment of vegetation is much slower. Even when the proper seeds are introduced from adjacent mountain tops the environment is inhospitable, and decades pass before the original introductions have formed an even moderately complete cover.

New areas of fumarolic activity appear to act first through a heating effect of the soil to which the native species are selectively tolerant. The emission of sulphur compounds creates an acid environment in the soil and air-borne acidic fumes. Natives species appear to be killed off in direct relationship to their ability to stand increasing acidity. The air-borne acid particles appear to be cumulative in their action on the surrounding vegetation. Ferns with leaves of delicate textures and broad-leaved plants without heavy cuticles are most sensitive to these fumes. Plants with coriaceous leaves or heavy cuticles are most resistant. At the highest elevations on soils composed of volcanic ash it is difficult to determine the role of fumarole emissions in the establishment and persistence of the species present.

In the Lesser Antilles the species which appear to be most tolerant of fumarolic gas emissions and soil acidity are the following: *Andropogon pertusus, Blechnum indicum, Cladium restioides, Clusia alba, Clusia mangle, Clusia plukenetii, Cyperus ligularis, Cyperus planifolius, Dicranopteris bifida, Guzmania plumieri, Lycopodium cernuum, Lycopodium meridionale, Lycopodium tortum, Philodendron giganteum, Pitcairnia angustifolia, Pitcairnia albucifolia, Pitcairnia spicata* var. *sulphurea, Pityrogramma calomelanos, Pityrogramma chrysophylla,* and *Ternstroemia peduncularis.*

A comparison of the plant species from other geographic areas which are tolerant of fumarolic environments or which are invaders of volcanically disturbed areas is interesting yet difficult due to the differences in composition of the floras. Much has been written of the thermal springs of the United States, particularly the area of Yellowstone National Park where emphasis has been given to heat tolerant algae and to the animal life of the hot springs. Similar studies are available for the hot-spring areas of Iceland. In both cases, the families, genera, and species of the plants can not be compared with those of the Lesser Antilles. The extensive fumarole areas of Indonesia and of Japan have received some study. Mizushima (41) studied the plant community of the fumarole areas of the Idzu Islands, midway between Tokyo and the Bonin Islands. He found that the plants tolerant of fumarole conditions were: *Chamaesyce hirta, Chrysanthemum pacificum, Cyperus polystachyos, Fimbristylis dichotoma* f. *floribunda, Imperata cylindrica* var. *koenigii, Lindernia crustacea, Lycopodium cernum, Lygodium japonicum, Ophioglossum petiolatum, Paspalum orbiculare,* and *Pouzolzia zeylanica* (Urticaceae). He noted that plants of *Lindernia crustacea* are of interest as the individuals gain in stature as they approach the fumaroles. *Hedyotis, Paspalum* and *Pouzolzia* were limited in their distribution on the island to the areas of the fumaroles. *Cyperus, Fimbristylis, Imperata, Lycopodium,* and *Lygodium* were indicated as abundant near the fumaroles.

The locations of the numerous areas of volcanism in Indonesia are effectively shown in a map published by Ter Braake (9). Braun-Blanquet (10) indicates that *Pteris incisa* thrives on the soft, sulphurous soils adjacent to springs that are rich in alum. *Polypodium vulcanicum* has been reported to survive on rocks which are occasionally flooded by waters with temperatures as high as 75° C. According to Holtermann (23), the dominant shrubs in such areas are *Agapetes vulgaris* and *Rhododendron retusum*.

Braun-Blanquet suggests that the plants of such fumarole areas are mesophytic in nature. Schimper (59) however, indicates that the flora of the solfatara areas is composed of xerophilous species. Zollinger (72) and later Junghuhn (34) were the first to observe in Java that the vegetation close to fumaroles was composed of alpine species, even when the fumarole was 1000 to 1500 meters below the natural alpine region. Schimper described the fumarole area as follows: "Where these pools are collected, usually in large numbers and of different sizes, the soil is a wet white clay, which is said by Junghuhn to arise by the action of sulphuric acid on trachyte; it is usually covered by a yellowish efflorescence of sulphur. The ground is frequently so hot that to remain standing on it is impossible. From all the crevices and pools there escape hot vapors of suffocating odour, sometimes of sulphuretted hydrogen, at other times of sulphurous acid. The water has an acid taste and sets the teeth on edge." He noted further that "the bushes of the solfataras are much lower in stature than the surrounding forest and quite sharply marked off from it. None of the small trees and shrubs that form the underwood in the high-forest appear among them; of forest herbs only a few species represented by detached individuals occur; plants that occur elsewhere in the open situations of the same region are entirely absent."

In the vicinity of solfataras Schimper indicates there are always numerous plants of *Ficus diversifolia*, *Rhododendron javanicum*, and *Vaccinum varingiaefolium*. In solfataras of lower regions some other species, notably *Gaultheria leucocarpa*, *Medinilla javanensis*, *Myrsine avenis*, *Rhododendron retusum*, and *Rhododendron tubiflorum*, occur, and, in addition, "isolated ferns with leathery leaves and lycopods are always present in such spots." Plants of the Melastomataceae and Myrsinaceae, although abundant in the Lesser Antilles, do not tolerate fumarolic environments. The Ericaceae are poorly represented in the Lesser Antilles, and the genera do not occur in areas where fumaroles are active.

Junghuhn noted that in solfatara areas the shrubs are swept clear of all epiphytic vegetation, including mosses and lichens. This is also true throughout the Lesser Antilles. A new fumarole seems to be most toxic to the epiphytic moss, liverwort, and lichen flora of trunks and branches of the adjacent vegetation. In dormant fumarole areas, however, mosses are among the first invaders.

The steam vents on Mauna Loa, Hawaii, contain minimal amounts of sulphur and do not seem to be influential in determining the vegetational components around them. Ferns, particularly *Nephrolepis*, are abundant, while *Dodonea*, *Styphelia*, *Vaccinium*, and many rubiaceous genera grow more vigorously in the humid environment of the vent than at a distance.

The revegetation of surfaces disturbed by volcanic eruptions has been the subject of a classic study in the case of Krakatoa (69). Fosberg (16) has outlined the nature of the invasion and revegetation of lava flows and ash-cinder areas of Hawaii. Only preliminary studies are available for the Parícutin eruptions in Mexico. Calvert and Calvert (12) discuss the effects of volcanic activity and subsequent fumarolic activity for Volcán Irazú, Costa Rica. However, the altitude and the species involved in all these areas do not permit comparisons with similar areas of the Lesser Antilles.

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EXPLANATION OF PLATES

PLATE I

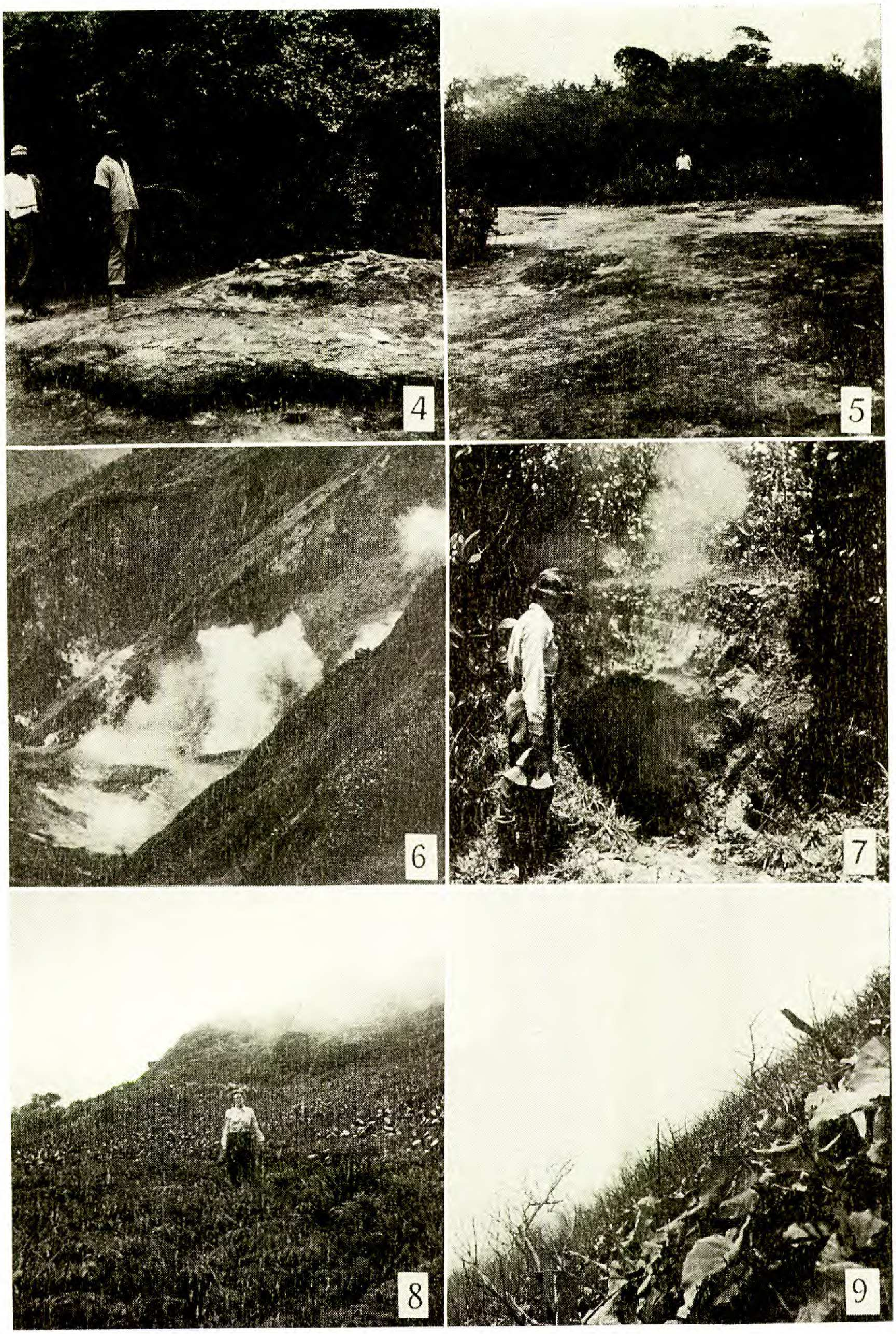
FIG. 4. Cone of fumarole at Lavera Hot Springs, Grenada. FIG. 5. Path of mineral deposit from cone in *Fig. 4*, Grenada. FIG. 6. Valley of Desolation, Dominica. FIG. 7. Steam vent at Wotten Waven, Dominica. FIG. 8. "Clusietum guadelupense" on windward slopes of La Soufrière, Guadeloupe. *Dicranopteris bifida* and *Cladium restioides* are seen in foreground, *Clusia mangle* in middle, and *Ilex* species on distant slope. FIG. 9. *The same* on leeward slopes, showing killing by periodic emissions of sulfur fumes. Dead plants are *Clusia*, *Ilex*, and *Freziera*; living plants are *Philodendron giganteum*.

PLATE II

FIG. 10. Gages Upper Soufrière, Montserrat, after its reactivation on November 11, 1935. Photo reproduced from Perret (45). FIG. 11. Gages Upper Soufrière, Montserrat, as it appeared in June. 1950. FIG. 12. Gages Upper Soufrière, Montserrat, as it appeared in January, 1961. FIG. 13. Dead and acid-rotted stump of *Sloanea dentata* at Gages Upper Soufrière in January, 1961. A fumarole had opened under this tree within the last decade, for the tree was alive in 1950. FIG. 14. Gages Lower Soufrière, Montserrat, in January, 1961. Vegetation has descended on the limonitized area from above. FIG. 15. Main steam vent at Galway's Soufrière, Montserrat, in January, 1961. Effect of the prevailing winds from the mountain is shown by the path of the steam. Effects of the fumes are visible on the hillsides by the reduction of vegetation.

PLATE III

FIG. 16. Lang's Soufrière, Montserrat, as seen from Paradise Ridge. Point of arrow locates the dead *Sloanea* trunk shown in FIG. 17. Rear of the arrow marks dense growth of *Philodendron giganteum*. FIG. 17. Point of emission of fumes from Lang's Soufrière, Montserrat. A dead trunk of *Sloanea* is on the left. Recent rock fall shows the depth of the effects of the acidity on the rock face. FIG. 18. A new area of fumarole activity at Gages Upper Soufrière, Montserrat, January, 1961. Plants of *Clusia alba* are in the foreground. *Cyathea* and other components of adjacent woodland are shown in the background, as yet, not affected by fumes of the new fumarole. Destructive effects to the present are due to heat and soil acidity. FIG. 19. Gages Upper Soufrière, Montserrat, January, 1961. The upper valley of this soufrière showing the proximity of the undisturbed woodland on the windward side of the fume area. FIG. 20. Qualibou Soufrière, St. Lucia. Boiling lakes and steam vents with acid-softened rock are in the foreground. The profile of the hill in the background shows the absence of shrubs or trees. FIG. 21. Qualibou Soufrière, St. Lucia. A face view of the hill shown in *Fig. 20*. The hillside vegetation is of *Blechnum* and *Lycopodium* where affected by the fumes of the soufrière. The edge of the affected area is shown on the right.



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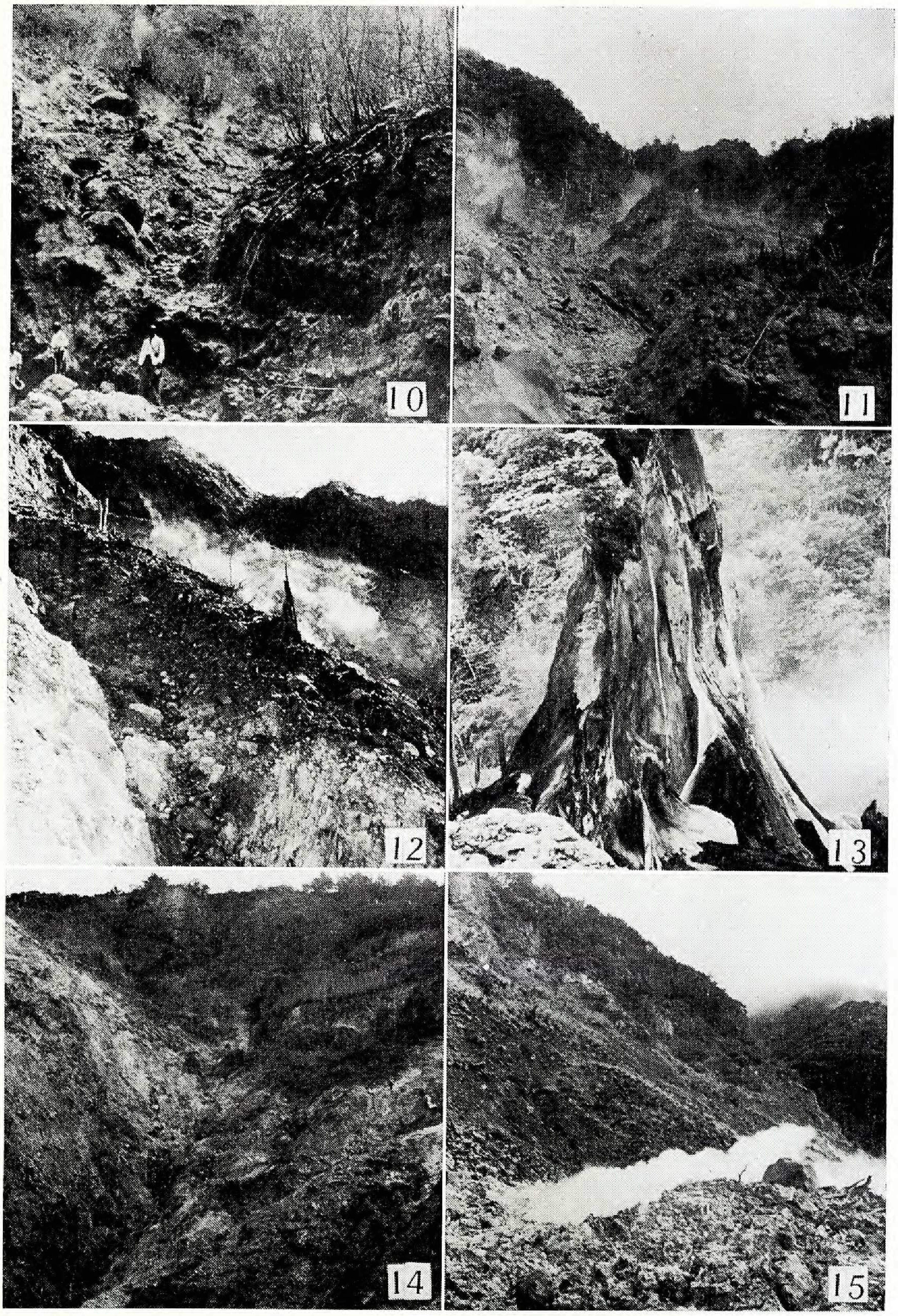

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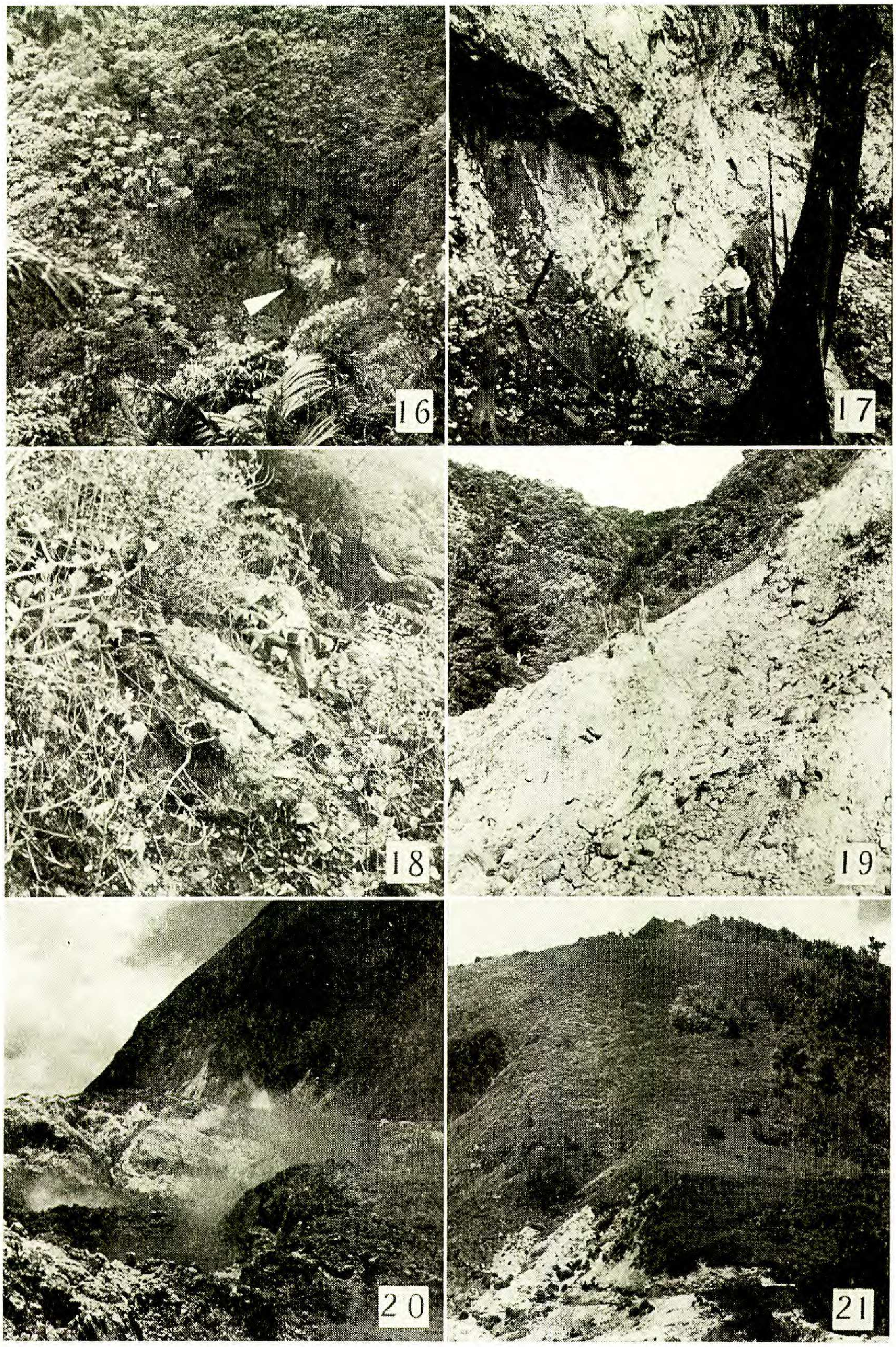

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